ISSUE STATEMENT

Crud deposition on PWR fuel can lead to cladding failure and crud induced power shift (CIPS), formerly known as axial offset anomaly (AOA). Higher energy cores resulting from longer fuel cycles, power uprates and more ‘efficient’ core designs cause more crud to deposit on the fuel than before these transitions took place.

During the period 2000 – 2010, two U.S. PWRs experienced crud-induced localized corrosion (CILC) failures and at least one other unit experienced clad wall thinning as a result of crud deposition. CILC is one of the least common failure mechanisms for PWR fuel; however, occurrences are difficult to predict and their impact can be large.

CIPS results from boron concentrating in crud in the upper spans of assemblies causing a power shift in the core. In severe cases, CIPS impacts shutdown margin and forced one plant to de-rate in the late 1990s. During the period 2000 – 2010, 12 U.S. PWRs experienced 23 reported cases of CIPS. CIPS has been experienced in European and Asian reactors as well.

Greater understanding of CIPS and CILC phenomena is needed to improve core designs and reduce risks to fuel reliability.

DRIVERS

Nuclear Safety
Fuel cladding is the first barrier to a fission product release to the general public and all reasonable actions to maintain the integrity of this barrier should be taken.

Radiological Factors
CIPS cycles have been linked to higher out-of-core radiation fields, which lead to higher worker dose. Failed fuel cycles often lead to more alpha inhalation events.

Operational Impact
CIPS cycles demand increased operator attention. Predicting core performance, reactivity management, and responding to normal power maneuvers and off-normal transients can be challenging. Outage durations may be affected by large crud bursts or fission product releases.

Costs
Costs associated with failed fuel include increased monitoring costs, additional fuel inspections, premature fuel discharge (and storage), and possible fuel reconstitution. For example, CIPS forced one U.S. PWR to de-rate for the final one-third of an operating cycle.

Industry Commitment
In 2006, utility chief nuclear officers pledged to support an initiative to drive industry to zero fuel failures (now referred to as “Driving to Zero”). This commitment remains in effect.

RESULTS IMPLEMENTATION

The program is designed to enable the development of core designs that minimize the risk for CIPS and CILC. This will be accomplished by introducing R&D results into fuel reliability guidelines and developing advanced modeling tools.

Updated Guidance
EPRI published the *PWR Axial Offset Anomaly (AOA) Guidelines*, Revision 1 in 2004 and Revision 0 of the *PWR Fuel Cladding Corrosion and Crud Guidelines* in 2008. These two documents provide the technical bases and recommendations for minimizing challenges related to CIPS and fuel cladding corrosion resulting from crud deposition. Because the mechanisms that cause the two phenomena are similar, the contents of both guidelines are being collated into a single document and will be revised periodically as R&D and operating experience warrant.

Advanced Modeling
EPRI’s Boron-induced Offset Anomaly Risk Assessment Tool (BOA) software product incorporates planned thermal hydraulics conditions, plant design information, and chemistry program information to predict crud deposition and boron uptake in the core. The code assesses the susceptibility of prospective core designs and chemistry programs to CIPS and CILC. BOA v3.0 was released in 2010 and R&D and benchmarking efforts continue so that improvements can be made in its predictive capabilities.
PROJECT PLAN

When new water chemistry technologies are developed to mitigate primary water stress corrosion cracking or to improve radiation fields, it is important to demonstrate that these technologies will have no adverse impact on fuel performance. To this end, EPRI investigates the effects of pH, lithium, zinc injection and elevated hydrogen on fuel cladding and various system processes such as deposition on fuel, ex-core material corrosion, and corrosion product transport. These projects take the form of laboratory testing, theoretical modeling and fuel surveillances with the intent that the results funnel into two principal products: advanced modeling tools (BOA) and the Guidelines.

Advanced Modeling

BOA incorporates plant design information such as steam generator tubing material and area, stainless steel surface area, system volumes, and cleanup system flow rates as inputs for a combined thermal hydraulic/chemistry model that calculates steaming rates, crud and boron deposition as a function of fuel elevation and time for all assemblies in the core. In addition, BOA modeling for individual fuel pins provides a method to assess CILC risk.

To improve BOA, research is planned to:

1. Estimate the general corrosion and release rates of metal from the steam generator tubing and stainless steel surfaces to characterize and quantify the crud sources,
2. Determine the properties and form of crud on the fuel clad, and
3. Measure crud scrapes and oxide thicknesses from fuel to compare the results to the predictions. Note that these efforts require utility support.

Reactor coolant chemistry also can have an effect on crud deposition. Zinc addition, changes in at-temperature pH programs, and elevated hydrogen operations are being applied to address corrosion and radiation fields, but these technologies can influence fuel performance. Moreover, these chemistry changes are being implemented in parallel with power uprates and longer cycles, which increase localized sub-cooled nucleate boiling and increase crud deposition on the fuel. The theoretical bases of BOA need to be expanded to include the new chemistries with the core design changes. For example, the interactions of zinc with nickel and iron precipitates at different hydrogen and pH values need to be fundamentally understood. This requires research support and several iterations of BOA model improvement.

Importantly, BOA model results require validation against plant data. Results obtained from visual inspections, crud scrapes, clad oxide measurements and out-of-core surface conditions will be combined with calculations and experimental results for the validation.

Future Guidelines Development

The PWR Fuel Cladding Corrosion and Crud Guidelines provide guidance for managing core design, chemistry and plant operations against cladding failure in the form of Mandatory, Needed and Best Practice recommendations. The PWR Axial Offset Anomaly (AOA) Guidelines provide similar guidance for CIPS prevention. The recommendations rely on the technical bases developed by EPRI’s Fuel Reliability Program as well as other EPRI programs (notably Chemistry and Radiation Management). These guidelines will be merged to provide a single source document for assessing risk and avoiding CILC and CIPS.

Several projects will assist in facilitating implementation of the revised Guidelines, including investigating the impact of zinc injection on crud deposition and morphology, understanding the effect of elevated hydrogen on zirconium alloy cladding, assessing the impact of elevated lithium on clad oxide films, and developing automated fuel visual inspection software.

RISKS

- From the time a new technology is introduced into a commercial reactor, there can be a long lag time to assess its impact or non-impact on fuel. PWRs are operating on either 18 or 24 month cycles and the “incubation period” of a problem could take six or more years (until the fuel is discharged). If the assessment requires fuel shipment and hot cell examination, analytical results could take an additional two years. Therefore, negative features of a new technology may not be revealed until after the technology has been applied several times in the same reactor or to multiple reactors.
- Many of the measurements, both poolside and laboratory, remain technically challenging; progress may continue to be slow in developing improved nondestructive examination techniques for crud and oxide thickness, along with hydrogen pickup in the cladding.
**RECORD OF REVISION**

This record of revision will provide a high level summary of the major changes in the document and identify the Roadmap Owner.

<table>
<thead>
<tr>
<th>REVISION</th>
<th>DESCRIPTION OF CHANGE</th>
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| 0        | **Original Issue:** August 2011  
**Roadmap Owner:** Jeff Deshon |
| 1        | **Revision Issued:** November 2011  
**Roadmap Owner:** Dennis Hussey |
| 2        | **Revision Issued:** August 2012  
**Roadmap Owner:** Dennis Hussey  
**Changes:** Based on feedback from the utility advisors and vendors, Axial Offset Anomaly (AOA) has been replaced with Crud Induced Power Shift (CIPS). Flowchart updated to include the Comanche Peak oxide measurement campaign, BOA version changes, and updates to the elevated hydrogen project. |
| 3        | **Revision Issued:** December 2012  
**Roadmap Owner:** Dennis Hussey  
**Changes:** Minor format changes. Flowchart updated to include BOA version schedule changes. |
| 4        | **Revision Issued:** August 2013  
**Roadmap Owner:** Daniel Wells  
**Changes:** Flowchart updated for project prioritization, project schedules, and interactions between programs. |